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THE APPLICABILITY OF DATA BASES ON COMBINED ENVIRONMENTAL EXTREMES FOR CALCULATION OF LOADS ON OFFSHORE STRUCTURES

ATMOSPHERIC ENVIRONMENT SERVICE

DOWNSVIEW, ONTARIO

1989

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FINAL REPORT

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ABSTRACT

The objective of the present study is to investigate the applicability of environmental data bases to the calculation of load combinations on offshore structures. The principal Canadian agencies which archive wind, wave, ice, current and earthquake data have been consulted. The nature and origin of the data, the spatial and temporal coverage and the quality control are assessed with the objective of determining the parameters required to perform load combination analyses. Software capabilities are appraised from the viewpoint of the quality and the efficiency of the output products, the availability of user-defined data set operations and the possibility of incorporating load combination techniques.

In order to determine load combination products that are at the same time conceptually correct and practical, the role of load combinations in structural design and decision-making is investigated. Both the technical literature as well as design codes have been studied in order to substantiate the recommendations regarding applied data analysis. A conceptual analysis of load combination shows that almost all data sets are applicable, the exceptions being ice data and current data where further physical re-modelling is needed.

Three possible work plans are suggested. Plan 1 is concerned with providing engineers with characteristic extreme values as well as appropriate companion values, for use in load combination rules. This approach is based on Turkstra's rule. The recommendations for Plan 2 refer to a more detailed picture of how loads are affected by the interaction of different environmental processes at a given offshore site. Results can be represented graphically in a practical design load combination diagram. Finally, Plan 3 revolves around the improvement, the development and the calibration of more efficient load combination rules.

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RÉSUMÉ

La présente étude vise à établir dans quelle mesure on peut se servir des bases de données environnementales pour calculer les combinaisons de charge des constructions au large des côtes. On a consulté les principaux organismes canadiens qui archivent les données sur le vent, les vagues, les glaces, le courant et les tremblements de terre. Afin de déterminer les paramètres nécessaires pour analyser les combinaisons de charges, on a évalué la nature et l'origine des données, la couverture spatiale et temporelle et le contrôle de la qualité. On a aussi évalué les capacités du logiciel sur les plans de la qualité et de l'efficacité des éléments de sortie, de la disponibilité des opérations des séries de données définies par les usagers et la possibilité d'incorporer des techniques de combinaison des charges.

Pour établir des éléments de combinaison de charge à la fois pratiques et corrects dans leur conception, on a étudié le rôle des combinaisons de charges dans les plans de construction et la prise de décisions. Pour appuyer les recommandations visant l'analyse des données appliquées, on a étudié les documents techniques et les codes d'étude. L'analyse conceptuelle de la combinaison des charges révèle que presque toutes les séries de données peuvent s'appliquer. Les seules exceptions sont les données sur les glaces et les courants, domaine où il faut poursuivre la remodélisaton physique.

On propose trois plans de travail éventuels. Le plan 1 vise à fournir aux ingénieurs des extrêmes caractéristiques, ainsi que des valeurs correspondantes appropriées, pour l'observation des règles de combinaison des charges. Cette démarche repose sur la règle de Turkstra. Les recommandations du plan 2 se rapportent à la représentation plus détaillée de la façon dont les charges subissent l'interaction des divers phénomènes environnementaux à un lieu déterminé du large des côtes. On peut représenter les résultats sous une forme graphique, dans un schéma pratique de combinaison des charges types. Enfin, le plan 3 s'articule autour de l'amélioration et de la mise au point de règles plus efficaces de combinaison des charges.

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1. INTRODUCTION

1.1 General Approach

The present report describes the results of an exploratory study of the use of Canadian meteorological and oceanographic data for engineering load combinations (LC). The objective of the study has been:

(a) to determine the requirements of structural engineers dealing with complex load combinations;

(b) to assess the feasibility of using the data sets to specify/improve/calibrate design load combinations for offshore structures.

Loads on offshore structures are caused by gravity, by operations including preloading, and by the environment. The design of the critical members in such structures is frequently governed by the environmental loads. Traditionally the design load is determined on the basis of a specified extreme value of the worst environmental process, e.g. waves, to which fractions of other loads, such as wind, current and ice loads, are added, in a rather arbitrary manner. Naturally, such conservatism has a detrimental impact on the economy of the structure. Design load combinations need to be formulated in such a way that they account for the reality of several environmental processes acting simultaneously, without resulting in an unacceptable reduction of the overall safety levels.

The approach to the study objectives is based on the following steps:

(1) An investigation of what the special role of load combinations is in structural design; why load combinations are so complex; and what the impact is on safety and economy.

(2) A critical assesment of load combination formats and criteria, using:
- technical literature;
- offshore design codes.

(3) An identification of the requirements of structural engineers dealing with LCs. This study should recognize that different needs exist, such as the need for practical, code-related values, the need for a more detailed environmental sensitivity study, and the general need to improve and develop efficient and practical LC rules.

(4) The derivation of a suitable set of load and environmental parameters associated with the requirements identified under (3). This step is particularly important, since the final output products must result from sound environmental analysis and must contribute meaningfully to structural design criteria.

(5) The identification of Canadian environmental data sets which can generate the parameters (4).

(6) An assessment of the feasibility of performing the recommended LC analyses using the data sets, and a discussion of additional data required and software development.

1.2 Nomenclature

The following is a list of symbols used in this report:

$c, c_1, c_2, \ldots c_i, \ldots$: structural influence coefficients (the ratio between load effect and environmental intensity), defined in (2.17).

$C, C_1, C_2, \ldots C_i, \ldots$: random (uncertain) structural influence coefficients.

D_i, d_i: random and particular value of an environmental process i.

E_i, e_{si}, e_i: random and specified value of the extreme of an environmental process i.

e_{ij}: companion value of the environmental process i with the principal process j.

f_A, F_A: probability density function (pdf) and cumulative distribution function (cdf) of the random quantity A.

f_{AB}: joint pdf of A and B.

g: non-dimensional extremal function (3.2).

p_f: annual probability of failure.

p_f^*: annual target probability of failure.

R, r, r_d, r_s: random, particular, design and specified value of the structural resistance.

r_{12}: correlation coefficient between two environmental processes 1 and 2.

R(x): return period of x.

t, T: time and time period.

u: utility.

X: random extreme load (effect).

x or x_s: specified combined load.

x_d: design load.

x_{ij}: companion load value of process i with the principal process j.

x^*:	Turkstra's specified load.
Y, y:	random and particular value of (point-in-time) load (effect).
$\dot{Y}$:	time derivative of load.
extr A:	a particular extreme value of process A(t).
max (A, B):	the largest of A and B.
α:	partial load factor.
γ:	probability reduction factor (2.15).
η:	annual exceedance probability.
λ:	ratio of the contributing load processes (3.15).
$\mu(A)$:	expected value of A.
μ_A:	mean of A.
$\nu_Y(\zeta)$:	mean upcrossing rate (per unit time) of the level ζ by the stochastic process Y.
σ_A:	standard deviation of A.
ϕ:	partial resistance factor.
ψ_{ji}:	companion factor (2.14), (2.16).

2. LOAD COMBINATIONS IN STRUCTURAL DESIGN

2.1 The Structural Design Problem

The objective of the present Section is to describe the structural engineering design process and to identify the analysis of environmental data as one of its key components.

Structural design is a decision process involving several uncertainties, the principal one of which is related to the unpredictability of the future state of nature. A good way to formulate the design decision problem is by using the notion of a game (Turkstra, 1970; Maes, 1986a) between two opponents: the designer (an individual, a body or a code authority) and "nature" (climate, bad workmanship, other unknown conditions). At stake are the safety and the profitability of the structure. The following general terms apply:

- a load is a (set of) force(s) applied to the structure by gravity, by deformations, by operations or by the environment, either by action or reaction.

- a load effect is the effect of a certain load at some point in a structural member, for example, the axial force in a concrete footing, the bending moment in a beam, or the transverse shear in a welded connection. (The term load is often loosely used instead of load effect.)

- the resistance is the ability of a structural member to withstand the load effect.

- failure is the condition reached when the load effect is greater than the resistance in a certain structure or structural member. This condition is undesirable and involves a particular type of loss to the designer.

In the design "game", the structural designer is faced with a number of decisions regarding the structure, the main one being: "How strong should the structure be made to resist the loads that are likely to occur during its lifetime?" Nature provides for the uncertainties in its game against the designer; first of all, the resistance is a random quantity which lies close to a design resistance value, which the designer has chosen; but, the greater uncertainty relates to the loads experienced by the structure, particularly the loads associated with the action of the environment.

A simplified version of the design decision problem is formalized in the decision tree of Figure 2.1. The designer has to choose between several design resistance values r_{si} (i = 1, n) and must make an optimal decision. If the design resistance (for example, specified in terms of the shell thickness, the amount of reinforcement or the concrete quality) is selected to be too small, then the structure will be exceedingly unsafe. Conversely, a large value of design resistance will lead to a very uneconomical design.

Suppose a particular resistance r_{si} is decided upon (Fig. 2.1), then the actual resistance is not necessarily equal to r_{si}, but is a random quantity R with a probability density function (PDF) $f_{R|\, r_{si}}(r|\, r_{si})$. It is "conditional" upon the selected r_{si}; this is indicated by the "$|\, r_{si}$" notation, which means "given r_{si}". Not only is the actual resistance R random, but so is the actual load X. Both random quantities characterize the "uncertain state of nature" that the designer is faced with.

To each combination of (selected r_{si}, actual resistance r_j, actual load x_k), we can ascribe certain consequences c_{ijk} (Fig. 2.1). The degree of satisfaction associated with c_{ijk}, is generally the product of many interacting evaluations and is expressed by the "utility" $u(c_{ijk})$. The object of utility theory (Raiffa and Schlaifer, 1968) is to formally analyze the preferences among each of the consequences, c_{ijk}. In the design problem we are concerned with here, a number of objectives can be identified, such as:

- a sufficient safety level;
- the undesirability of overdesign and associated costs; and
- the undesirability of environmental loading in excess of a certain level.

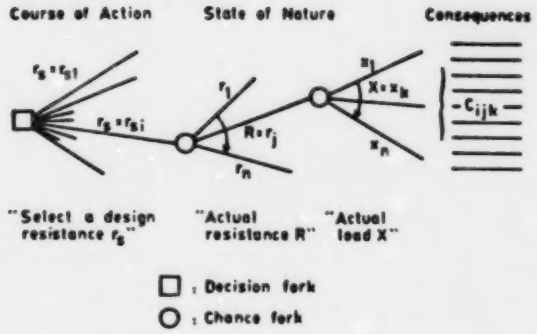


Fig. 2.1. Analysis of a Design Decision

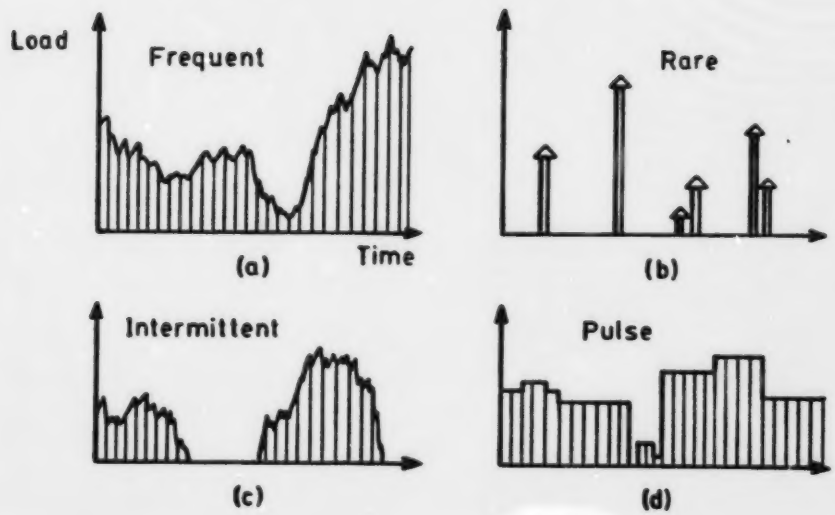


Fig. 2.2. Load Processes

The complexity of the decision problem is greatly reduced by expressing the consequences in terms of a single number, namely the annual probability of failure p_f:

$$p_{fi} = Pr\ (X > R | r_{si}) \tag{2.1}$$

The advantage is that to each possible design choice r_{si} corresponds a probability of failure p_{fi} which is equal to the probability that the total load effect X exceeds the resistance R during one year. Furthermore, by specifying a <u>target</u> value p_f^*, which embodies the best compromise between economy (which increases with increasing p_f values) and safety (which increases with decreasing p_f values), it is possible to make an optimal design decision by determining the value of r_{si} for which equation (2.1) with $p_{fi} = p_f^*$ is best satisfied.

In general, the procedure described above requires detailed probabilistic information about all the loads that contribute to the load effect X in the structural member, as well as the structural resistance R. The modelling of the latter variable is a routine statistical exercise, because plenty of data are available which describe variations in strength, geometry and workmanship for a wide range of structural members (references are contained in Maes (1986a,b)). The probabilistic modelling of loads on offshore structures in Canadian waters is much more difficult on account of the much greater uncertainty associated with loads. The coefficient of variation of typical extreme loads for example, is typically in the order of 0.3 to 0.4 (Maes, Muir and Swail, 1987), while the same coefficient is only about 0.1 for resistance. At the same time, statistical data regarding loads, particularly those associated with the environment, are often scarce and/or fail to cater to the needs of design engineers. Consequently, appropriate environmental data analysis is probably at the present time, the process which can contribute most to the optimization of structural design decisions.

2.2 Loads and Load Combinations

Loads acting upon a structure can be subdivided into several categories, depending on how they are manifested in time:

1) frequent load processes, such as wave or wind loads, which can be represented by continuous stochastic time series (Fig. 2.2a).

2) rare load events or processes, such as earthquakes, iceberg impacts and accidental loads, which occur at discrete points in time (Fig 2.2b).

3) intermittent processes, such as sea sheet ice or snow loads, which have alternating active and non-active periods in time (Fig. 2.2c).

4) pulse or near-pulse type processes, such as gravity and operational loads (Fig. 2.2d).

Since the reliability of the structural system is measured against the annual target probability of failure, it is clear from equation (2.1) that the total load X must represent the maximum load which occurs during any given year. Indeed, we have:

$$\begin{aligned} &\text{Pr (All Loads During One Year} < \text{Resistance)} \\ &\qquad = \text{Pr (Maximum Annual Load} < \text{Resistance)} \end{aligned} \tag{2.2}$$

As a result, the designer is interested in the (annual) extremal probability distribution of the total load effect: $F_X(x)$. If it is possible to obtain this function, then the annual probability of failure is simply equal to:

$$P_f = \int_0^\infty (1 - F_x(r))\, f_R(r)\, dr \tag{2.3}$$

where $f_R(r)$ is the known probability density function (PDF) of resistance.

At first sight, the selection of a one year period of time as a reference long-term time span might seen somewhat arbitrary. Although other reference time spans, such as the estimated lifetime of the structure, would perhaps be appropriate, the distinct advantage of the per annum choice is that return periods R(x) are scaled in units of years. For example, the load with a 0.05 exceedance probability on the one-year extremal PDF of load, has a 20-year return period. Recall that:

$$R(x) = \frac{1}{1 - F_X(x)} \tag{2.4}$$

In most practical cases however, the complicated design procedure outlined above is avoided. This procedure would involve full probabilistic modelling of the total load effect probability distribution as well as making an optimal design decision regarding resistance by calibrating (2.3) against a target value p_f^*). Only the design of a sizable project involving critical economical and/or safety considerations may warrant the application of a full probabilistic analysis. The majority of design decisions, particularly those involving standard structures subjected to routine loading, are made using codified design rules. In a structural design code, the design resistance of a particular member is directly specified on the basis of certain design load values which are combined (added and factored) according to a clearly prescribed set of rules.

First we shall consider the simple case of a single load, for example a single wind load acting on a cantilever beam. The following is a step by step outline of the design procedure specified in modern design codes and applied to the wind loading example. The procedure is referred to as the "Partial Factor Design Format" because constant factors are used in Steps 4 and 6 to determine the design values of load and resistance.

Step 1: Collect environmental data, D, for the design site and determine the (annual) extreme wind speed probability distribution. In the following, the magnitude of individual environmental events and extreme environmental events will be denoted by D and E respectively. Particular values of these two random processes will be denoted by lower case symbols: d and e.

Step 2: Determine the code-specified characteristic value, e_s; in most of the recent design codes a one hundred year return value is used; as a result, the extreme wind speed with an exceedance probability of 0.01 would be selected.

Step 3: Determine the load, x, associated with the environmental extreme value, e_s; design codes generally deal in great length with this step. In the present case, the obtained wind pressure is assumed to be the only load acting on the structure, and therefore, it constitutes the specified load, x_s.

Step 4: Multiply the specified load by load factor α, to obtain the design load, x_d:

$$x_d = \alpha\, x_s \tag{2.5}$$

In the case of a single loading, the load factor α is generally equal to about 1.3. In load combination rules, however, α may vary between 0.5 and 2.0 (see subsequent discussion). Next, determine the design load effect corresponding to the design load. In the present example, the design bending moment is highest at the base of the cantilever beam and is equal to the resultant of the design wind pressure multiplied by its lever arm. In the present study, we will make the very reasonable assumption that load effects and loads are linearly related. As a result the multiplying constant between load and load effect can be absorbed in a previous step, say Step 3; there is then, apart from a scaling factor, no difference between loads and load effects.

Step 5: Select the design resistance, r_d in such a way that it is at least equal to the design load x_d:

$$r_d = x_d \tag{2.6}$$

Naturally a higher value of design resistance is allowable from the viewpoint of safety, but the design then becomes increasingly uneconomical.

Step 6: The specified resistance, r_s is obtained by applying a resistance factor ϕ to the design resistance:

$$r_s = \frac{r_d}{\phi} \qquad (\phi \leq 1.0) \qquad (2.7)$$

In short, the lengthy iterative procedure to determine the optimal design solution is replaced by a set of rules in which partial factors and characteristic values for load and resistance are clearly specified (Fig. 2.3). Calibration of a design code involves the calculation of the partial factors so as to fulfil the safety requirements optimally.

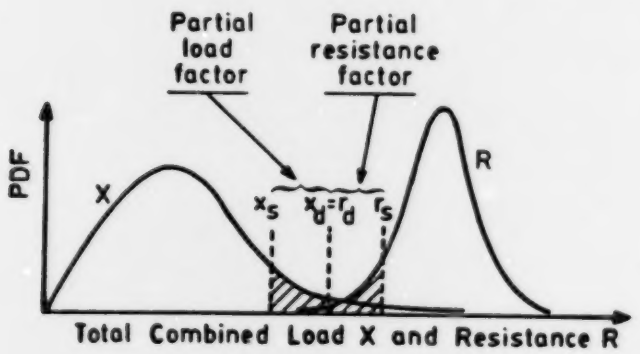


Fig. 2.3. Schematic of Partial Factor Design Format

Whereas the above procedure for a single load is comparatively straightforward the design against more than one load acting in combination poses much greater difficulties. Steps 1, 2 and 3 of the partial factor design procedure need to be subdivided down and new combination rules formulated in order to determine the specified load, x_s (the continuation of the procedure remains the same). A critical assessment of LC formats and rules is given in the following section.

2.3 Load Combinations, Formats and Rules in Offshore Codes

The criteria for load combinations are among the most intricate and contentious issues in design codes. The likely cause for this unfortunate situation can be ascribed to:

(1) the complexities associated with formulating the interaction between different loads processes;

(2) the difficulty to describe the resulting load combinations using a design code format which is practical, efficient and simple;

(3) the tendency to use excessively conservative LC design rules, in order to "make up" for the inadequacies associated with (2).

In the following discussion, the terms sum and addition will refer to the appropriate vectorial sums of loads.

In 1970, Turkstra provided an intuitive and appealing approach to the combination of n loads X_i (i = 1, ..., n). It consists of considering only certain points in time likely to be of major importance, namely those points at which each individual load X_i attains its "extreme" value, the remaining loads X_j ($j \neq i$) taking on "companion" values. The terms "extreme" and "companion" can be interpreted in different ways, as will be discussed subsequently, but essentially, the first three steps of the 6 step procedure described in Section 2.2 are modified as follows:

Step 1: Collect data for each type of environmental action: $D_1, D_2, \ldots D_n$. Determine also each annual extreme environmental probability distribution: $E_1, E_2, \ldots, E_n$.

Step 2: Determine for each type of environmental action i:

a) a characteristic extreme value, e_{si}, as in the single load procedure (e.g. at a specified extreme exceedance probability); e_{si} is occasionally referred to as the "principal" value of the process.

b) a set of n-1 companion values e_{ij}, where j takes on all the load index values except for i itself; e_{ij} is to be used as a value of process i which accompanies a principal value of the process j.

Step 3: Determine the load corresponding to the combined action of each principal process i in turn, acting together with its companion processes. The greatest of these load values is the specified load, x_s:

$$x_s = \max_i \left(x_{si} + \sum_{j \neq i} x_{ji} \right) \tag{2.8}$$

Steps 4, 5, 6: Remain unchanged.

It is worthwhile illustrating this procedure in the case of three environmental load processes: wind D_1, waves D_2 and sheet ice loading D_3. There are three extreme values e_{s1}, e_{s2} and e_{s3}, and one companion value e_{ij} is to be determined for each two by two combination (i,j):

i = 1 wind	: e_{s1}, e_{12} (to be used with wave),	e_{13} (to be used with ice)
wind load	: x_{s1}, x_{12}	x_{13}
i = 2 wave	: e_{s2}, e_{21} (to be used with wind),	e_{23} (to be used with ice)
wave load	: x_{s2}, x_{21}	x_{23}
i = 3 ice	: e_{s3}, e_{31} (to be used with wind),	e_{32} (to be used with wave)
ice load	: x_{s3}, x_{31}	x_{32}

The specified load, x_s, is then equal to largest of the following three combinations:

$$x_s = \max \begin{pmatrix} x_{s1} + x_{21} + x_{31}, \\ x_{12} + x_{s2} + x_{32}, \\ x_{13} + x_{23} + x_{s3} \end{pmatrix} \qquad (2.9)$$

Critical in the use of the Turkstra format is, of course, the exact definition of all the companion process values (and/or companion loads) that are used in the combinations. In the existing offshore design codes only sporadic guidance is given. NPD (1985), for example, recommends that the total load combination be specified as the most probable largest in 100 years. In fact, the designer is not explicitly made aware of Turkstra's principle: he must arrange for himself to find the combination that gives maximum total load. This recommendation is certainly too general and although it provides plenty of freedom, it gives little assistance to the designer. Probabilities related to the simultaneous action of environmental loads are allowed to influence the value of load combination in DnV (1977). However, except for wind and wave no practical suggestions are provided. (The companion wind is to be determined using a 1-minute sustained wind speed, rather than the 3-second gust normally used for the extreme wind.) A literal interpretation of the DnV code specifications would result in taking all specified environmental loads at the 0.01 annual exceedance level, regardless of their use as exceptional or companion values. FIP (1983) recommends that exceptional values and companion values be specified at the 0.01 and 0.50 annual probability of exceedance levels, respectively. However, the 0.50 value is not related to a specific time interval (probably a per annum value is intended). In 1986, the CSA

Technical Committee S471 tentatively suggested that the normal value of companion loads, independent of the primary load, be equal to the one-month median which, for frequent loads, corresponds roughly to a 99.97% probability of exceedance in one year. But in the most recent (tenth) draft of the CSA S471 Standard for fixed offshore structure, companion processes are classified into three groups denoted as follows:

d: a companion process that is dependent on, or has some correlation with the principal process;

i: a companion process that is stochastically independent of the principal process;

0: the companion process does not, with any significant magnitude, occur simultaneouly with the principal process and may therefore be omitted from combination.

A table is provided to give guidance regarding which processes need to be considered and to which of the above three groups they belong. It is duplicated in Table 2.1. The standard further specifies the characteristic values of the companion processes:

for d: this may be determined on the basis of an annual probability of exceedance of 0.01.

for i: The annual extreme value, e_{95}, with a probability of exceedance of 95% (i.e. at the lefthand side of the distribution).

for 0: Zero.

Table 2.1. Companion Processes in the CSA S471 Standard (Tenth Draft)*

Principal Process or rare event	Companion Process				
	Waves	Wind	Wind Driven Current	Other Current	Sea Ice
Waves	-	d	d	i	o
Wind	d	-	d	i	o
Wind	o	-	d	i	d
Other Current+	i	i	i	-	d
Sea Ice	o	d	d	d	-
Earthquake	i	i	i	i	?
Icebergs, or isolated ice floes	i	d	d	d	o

* Nine explanatory comments accompany and form a part of this table in the CSA S471 draft.

? The S471 draft states "The effect of sea ice coverage on the response of the structure to earthquake" should be given special consideration.

+ This does not include wind-driven currents, which are assumed in S471, as a first approximation, not to be a principal process.

In fact, the previous specifications reflect that the companion value e_{ij} of the process i can be related to the mean of the conditional probability of the process i, given that the principal process j takes on its specified extreme value e_{sj}:

$$e_{ij} = \mu\,(D_i \mid D_j = e_{sj}) \tag{2.10}$$

where $\mu\,(\cdot)$ denotes the expected value, or the mean, of the random quantity within brackets; as mentioned before, d and e are particular values of the individual and extreme random quantities D and E, respectively. Formula (2.10) may be applied to the three companion process groups:

- if the processes j and i are mutually exclusive, then clearly:

$$X:\ e_{ij} = \mu\,(D_i \mid D_j = e_{sj}) = 0; \tag{2.11}$$

- if the two processes are stochastically independent, then

$$I:\ e_{ij} = \mu\,(D_i \mid D_j = e_{sj}) = \mu\,(D_i), \tag{2.12}$$

that is, the companion value is not an extremal value but is equal to the mean value of process j at any arbitrary point in time (i.e. the value that would be measured if the process would be sampled at an arbitrary point-in-time). Unfortunately, design engineers are somewhat hesitant to use a mean point-in-time value in the context of code specifications. There are two reasons for this:

(1) an additional, complicated analysis of environmental data is required; often, point-in-time data are not readily available.

(2) the load caused by the companion point-in-time value may be very small in comparison with the extreme value of the principal process; is there sufficient reason to perform a time-consuming analysis for a virtually negligible load?

Thus, for reasons of practicality, the companion value of a stochastically independent process is presently specified on the basis of the annual extreme distribution, which is needed anyway to determine the specified extreme value when the process acts as a principal one. The large exceedance probability (95%), at which the companion value is specified, is somewhat arbitrary; it is merely intended to represent "a" small value, somewhere close to the point-in-time mean. The implications on the safety and the economy of the structural design are unclear.

- if the processes are stochastically and/or physically dependent, then formula (2.10) indicates that the conditional mean is required, given that the principal process acts at its extreme value. Not only are the majority of environmental events contained in this category (as witnessed by the "C"s in Table 2.1), but the procedure also involves the most critical thinking and modelling. For example, the determination of the joint pdf for waves and wind from which the conditional pdf of wind given extreme waves can be derived, is not an easy matter. Even on a theoretical level, there is little agreement regarding model selection and data treatment. Faced with these difficulties, designers generally choose the following practical but (in most cases) very conservative approach: if the processes are dependent, then <u>full</u> linear dependence (hence, a correlation coefficient of +1) is assumed; in (2.10), the expected value of the companion process i is consequently equal to its own specified extreme value, as if it were acting as a principal process:

$$D: \quad e_{ij} = \mu\,(D_i | e_{sj}) = e_{si} \tag{2.13}$$

This simplication is also reflected in the clause for <u>dependent</u> companion processes contained in the CSA S471 standard: "For the calculation of specified extreme loads, the companion value shall be characterized at a

value with an annual probability of exceedance of 0.01 (i.e. full linear dependence).

The present section has focussed on the discussion of load combination formats structured according to Turkstra's principles. For sake of completeness, it must be mentioned that other formats have been implemented in design codes. Turkstra and Madsen (1980) point out that the essential difference between previous (before 1980) basic code formats was whether they multiply factored design loads by combination factors before or after summation. An example of the former practice is the companion factor approach (e.g. used by CEB 1975), while the latter procedure is illustrated by the probability reduction factor approach (e.g. used by the National Building Code of Canada). The factored load effect αx_s, where x_s is the prescribed environmental load (Step 3) and α the load factor (2.5), is substituted by the following expressions, where ψ_{ji} and γ are factors less than unity, representing the reduced probability of simultaneous occurrence of load peaks:

- companion factor approach:

$$x_d = \alpha^* x_s = \max_i \left(\alpha_i \, x_{si} + \sum_{j \neq i} \alpha_j \, \psi_{ji} \, x_{sj}\right) \qquad (2.14)$$

- probability reduction factor approach:

$$x_d = \alpha^* x_s = \gamma \left(\sum_i \alpha_i \, x_{si}\right) \qquad (2.15)$$

The companion factor approach shows a slight similarity with Turkstra's format (2.8); in fact, if all the load factors α_i would be identical, then each companion process value x_{ij} is equal to:

$$x_{ji} = \psi_{ji} \, x_{sj}, \qquad (2.16)$$

that is, the companion load value associated with process j is prescribed as a fraction ψ_{ij} of the specified extreme x_{sj} of process j. Of course, this approach is very practical since it requires only one extreme value x_{sj} per process to be prescribed together with a matrix ψ_{ij} covering all the companion load values. However, the method presupposes that each type of process possesses a unique ψ_{ij} factor which is independent on local meteorological and oceanographic conditions; it essentially assumes that the ratio between the extreme value x_{sj} and the conditional mean (2.10) is always constant.

For the same reason, it is also clear that the probability reduction factor approach (2.15) is not satisfactory from the viewpoint of consistent risk: the extremes of all the processes are added and subsequently reduced by an arbitrary factor which fails to recognize the physical behaviour of combined processes.

2.4 Literature Review

Technical literature has dealt extensively with the problem of combining the load effects associated with two or more stochastic processes. Almost all the results obtained are developed for stationary and stochastically independent processes. In that case Rice's formula can be used to calculate the expected number ν of (positive) upcrossings of a (high) level ζ per unit time of the load process (Thoft-Christensen and Baker, 1982)

$$\begin{aligned} Y(t) &= Y_1(t) + Y_2(t) + \ldots \\ &= c_1 D_1(t) + c_2 D_2(t) + \ldots \end{aligned} \tag{2.17}$$

where Y_1, Y_2 ... are the contributing load (effect) processes associated with the environmental processes D_1, D_2 ...; since linear load effects have been assumed, Y_i and D_i can be related by constant structural influence coefficients c_i. The mean upcrossing rate ν of the combined process is:

$$\nu_Y(\zeta) = \int_0^\infty \dot{y} \, f_{Y\dot{Y}}(\zeta, \dot{y}) \, d\dot{y} \tag{2.18}$$

where $f_{Y\dot{Y}}$ is the joint pdf for the process Y(t) and its time derivative $\dot{Y}(t)$. When Y(t) is a sum of processes (2.17), $f_{Y\dot{Y}}$ can be derived on the basis of the well known elementary convolution integral for a sum of random quantities. For example, in the case of just two variables Y_1 and Y_2, the pdf of their sum Y is equal to:

$$f_Y(y) = \int_{-\infty}^{+\infty} f_{Y_1}(y_1)\, f_{Y_2}(y - y_1)\, dy_1, \tag{2.19}$$

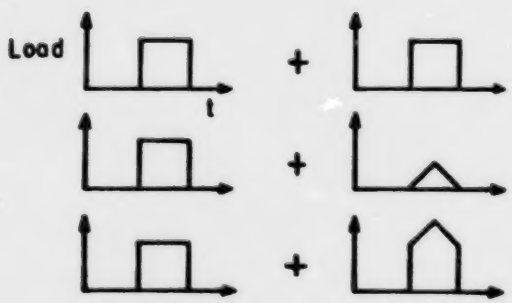
with similar expression for $f_{\dot{Y}}$ and $f_{Y\dot{Y}}$. Subsequently, the mean upcrossing rate $\nu_Y(\zeta)$ can be transformed into the extremal distribution F_x of the combined load effect X, where,

$$X = \max_T Y \tag{2.20}$$

and T is a reference period of time of one year:

$$F_X(\zeta) = \exp\,(-\nu_Y(\zeta)T) \tag{2.21}$$

Unfortunately, the mean-upcrossing rate $\nu_Y(\zeta)$ can only be derived approximately, using upper bound simplifications and asymptotic expressions. This topic has been the object of several studies, an excellent review of which is given in Madsen et al (1986). Madsen, Kilcup and Cornell (1979) calculate (2.18) for sum of two pulse-type processes of the type:



(2.22)

In fact, this is an extension of an approach proposed initially, see Wen and Pearce (1981, 1983), to simplify stochastic load processes into a series of rectangular Poisson pulse events as illustrated in Fig. 2.4 Bosshard (1975). Further refinement was introduced by Larrabee and Cornell (1979 and 1981). They derive a simplified expression for the mean upcrossing rate (2.18) of the process $Y = Y_1 + Y_2$, of the following form:

$$\nu_Y(\zeta) \approx \int_{-\infty}^{+\infty} f_{Y2}(y)\, \nu_{Y_1}(\zeta - y)\, dy + \int_{-\infty}^{+\infty} f_{Y_1}(y)\, \nu_{Y_2}(\zeta - y)\, dy \qquad (2.23)$$

This formula shows that ν_Y can be calculated approximately as the sum of two convolution integrals which require the knowledge only of the two point-in-time pdfs f_{Y1} and f_{Y2} and of their extreme value distributions F_{X_1} and F_{X_2}, which, by virtue of (2.21) are related to the mean upcrossing rates ν_{Y_1} and ν_{Y_2}. In the 1979 paper, they show that (2.23) is always on upper bound for the mean upcrossing rate (2.18); moreover, they prove that (2.23) is actually exact for the combination of the processes depicted in Fig. 2.5, but not for other combinations (for example, the error on the sum of two house pulse shapes as shown in (2.22) is maximally 33%).

Larrabee and Cornell (1981) investigate the implications on partial factor design formats. In a very elegant analysis, they point out that Turkstra's rule (2.8) provides a code format with load variables consistent with the probabilistic solution for combined loading (2.23). While they also point out some minor shortcomings of the Turkstra format, their finding is restricted to stationary, independent processes (but processes of any type: frequent, rare, pulse, ...). Their theoretical analysis also enforces the use of a set fractile level of the arbitrary point-in-time load in the case of a combination of stochastically independent processes; this is in agreement with (2.12), where the mean point-in-time value was suggested as companion value. Unfortunately, while Turkstra's principles are intuitively appealing and theoretically justified, they do not specify the fractile values of the individual loads (both on the extreme and the point-in-time load) necessary to achieve a set fractile value of the total load effect. This important point is one of the key considerations in load combination design.

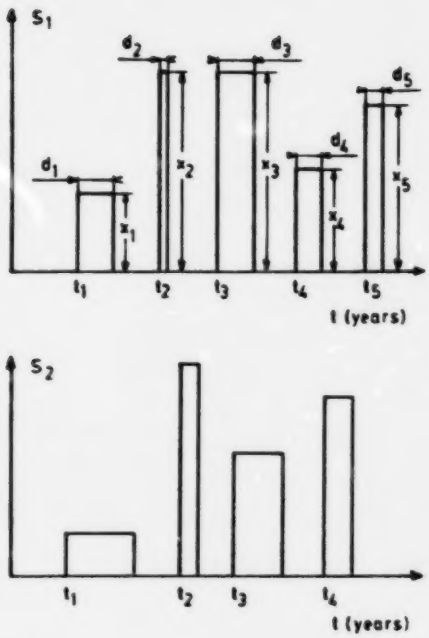


Fig. 2.4. Wen's Poisson Pulse Model for the Sum of Two Processes S_1 and S_2

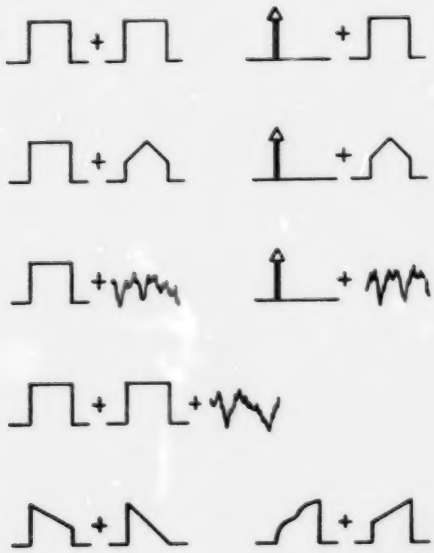


Fig. 2.5. Examples of Sums of Processes for which (2.23) is the Exact Mean Upcrossing Rate

Turkstra and Madsen (1980) focus on specific load processes (wind, live load, snow, earthquakes) using the Borges - Castanheta (1972) models (repetitive retangular pulse processes). This mathematical simplification allows several combination design formats to be investigated. Conclusions relevant to the present study include:

- Design combination rules depend on the probability level at which comparisons are made. In general, the more unlikely the exceedance of the design values of individual loads, the less important the combination problem.

- The uncertainty in load models is of major importance in the study of individual loads. However, results for the combination of loads are relatively insensitive to the load models used.

- Simple addition of design loads can lead to very conservative results. Ignoring load superposition can lead to extremely nonconservative results.

- The probability reduction factor approach (2.15) led to significant errors in a number of cases.

- The companion action approach coupled with a simple conceptual model and with well chosen numerical values led to design values almost always within 10% and normally within 5% of theoretical values in the cases studied.

A different approach is based on second-moment reliability formulations which require only the means and variances of the individual stochastically independent loads. Der Kiureghian (1979) applies this method to simple load processes and compares it to full solutions obtained using Monte-Carlo simulations. Agreement is generally good.

Throughout this study, we have assumed that, in developing LC methods and rules, we must ensure that the probability of exceedance of a sum of loads is approximately equal to the probability of exceedance of any load acting separately (Larrabee, 1978). The latest UK draft guidance notes (Dept. of Energy, 1987) warn against the uncritical application of this principle. They note that many safety factors are implicitly built into design procedures, so that a required overall safety level is achieved which is considerably higher than the one associated with explicit probabilities of failure. One important set of implicit safety factors is that which is introduced by making conservative assumptions about the manner in which individual loading parameters act in combination (e.g. by making no allowance or only limited allowance for joint probabilities). The removal of these implicit safety factors, through the fuller use of joint probability considerations within the deterministic framework, is therefore justified only to the extent that it is clear that overall safety is not jeopardized. This fact must be kept clearly in mind when supplying companion environmental values to design engineers. The guidance notes also contain an interesting analysis of the combination of:

- waves, sea levels and currents;
- winds, waves and temperatures.

Battjes (1979) develops a method to formulate the response probabilities due to a combination of environmental conditions. He concentrates on the offshore and assumes that a sea state can be characterized by a set of parameters such as significant wave height, mean wave period, and wave direction. An extreme combined sea state can then be found by considering the occurence rate of all the severe storms. This approach is attractive in that it can be extended to include parameters such as wind speed and current speed, thereby allowing practical extreme load combinations to be derived.

Mansour (1981) is interested in the combined bending stresses in ships due to waves, stillwater loads and thermal loads. His analysis is entirely in the frequency domain and considers correlations between the different load components. He indicates how the approach could be used to derive extreme values for design, but restricts the discussion to theoretical considerations.

Naess (1985) presents a rather rigourous analysis of the extreme values of combined loading due to wind, wave and currents in a stationary sea. The parameters of this (severe) sea state are specified a priori, using the concept of a design storm. For example, the wave spectrum, the wind and current speed distribution parameters should be given as sea state characteristics. Consequently, the study focuses on the extreme load effect within such a combined sea state. Model uncertainties (eg in Morison's hydrodynamic force equation) can be accounted for.

In conclusion, the literature on load combinations covers a wide range of specialized topics. Very few papers are concerned with providing practical solutions to the complex problem of specifying load combination values for offshore engineering design. However, the three or four papers that do address this point show that:

- there is no clearcut mathematical procedure available to derive load combination rules/values which covers all types of processes and loadings.

- the Turkstra format is empirically acceptable, even if there exist no guidelines for the characteristic values required in the associated LC design rules.

- practical companion values for independent processes are to be based on point-in-time probability distributions.

- load model uncertainties must be taken into account, the most prominent ones being associated with the transition from environmental process to load process.

- conservatisms in present LC rules must be recognized and investigated in terms of their contribution to overall safety.

2.5 Requirements for Engineers

It has been shown that the formulation of load combinations involves many technical and conceptual difficulties. Presently, no unified methodology exists for

determining exact design LCs. Approximate techniques are available in some specific cases, but even there, the required detailed analysis is so excessive that it tends to preclude their use by design engineers. Consequently, the following questions arise: in what way can environmental data analysis contribute meaningfully to LC design, and, exactly which data products can be of practical benefit to structural engineers? The discussions in the previous section demonstrate clearly that the answer to these question is to be sought on different levels. It is recommended that environmental data products/analysis address the following engineering needs:

REQUIREMENT 1: Spot Check Design Values

In many cases, there is an immediate need to obtain environmental design values for a given offshore location. This is often the case when the engineer is confronted with a preliminary design and wants to investigate the overall/specific structural configuration of his/her concept; alternatively, the engineer might be interested in the sensitivity of a structural dimension/strength to an environmental variable.

The data product needed consists of a characteristic extreme value together with a set of companion values for each environmental process requested by the user. These values can be plugged directly into LC rules from existing design codes, to obtain design load effects.

REQUIREMENT 2: Combination Statistics

When there is a need for more detailed structural analysis, either because the design is in a more advanced stage, or else, because the structural member under consideration performs a critical role in resisting environmental loadings, then the parameters provided under (1) need to be supplemented by more specialised statistical information, such as:

- additional extreme values determined at different probability levels
- marginal means and variances

- conditional means and variances, given the value of other environmental processes
- occurrence rates of extreme or severe environmental conditions
- point-in-time means, variances and fractiles
- correlation data

Essentially, the engineer needs a global picture of environmental conditions and interactions between processes, one that goes beyond the simple requirements imposed by the design codes.

REQUIREMENT 3: Improvement of LC Design Rule and Calibration

The preceding sections in this chapter have illustrated that there is a great need to develop and calibrate appropriate load combination design criteria. The Canadian Offshore is particularly suitable to be subjected to such a process because:

1) The Canadian Standard Association presently contains a very flexible and appropriate version of the Turkstra format to deal with load combinations. The S471 Standard will continue to function as a preliminary standard for the next few years and will consequently remain open to meaningful improvements of LC design criteria.

2) The Canadian data agencies are particularly well equipped to undertake a site-by-site analysis and calibration (Chapter 4).

The products required include full probabilistic models, such as the parameters of joint probability distributions and/or marginal and conditional distributions.

The work plan which corresponds to these three engineering requirements similarly consists of three basic tasks; they are listed in Table 2.2. In Chapter 3, we will identify exactly which metocean parameters are associated with the three requirements, using a conceptual probabilistic analysis of the combination of load processes.

Table 2.2

Work Plan Associated with the Engineering LC Requirements

TASK 1	To generate Spot Check Design Values (extreme and companion values), for use in connection with design codes.
TASK 2	To generate detailed Statistical LC Parameters related to the metocean environment.
TASK 3	To develop probabilistic models of joint environmental processes, with the objective of improving/developing/calibrating LC design criteria.

3. ENVIRONMENTAL LOAD COMBINATIONS

3.1 A Conceptual Model for Load Combinations

Ideally, load combinations should be dealt with by applying the theory of stochastic processes, which accounts for the stochastic nature and correlation of individual load processes in time and space. Subsequently, extremal analysis and other advanced probabilistic techniques should be used to determine the design combined load effect. As illustrated by the review of codified and technical literature on the subject of L.C., this approach meets with major difficulties and lies beyond the scope of this study. Therefore, considerable simplifications must be introduced in order to analyze load combinations on a practical level. On the other hand, the analysis must be sufficiently conclusive with regard to the nature of the parameters recommended in this study.

As a result, the following simple analysis has been attempted. It relies on the assumption that all the individual environmental processes D(t) can be considered to be stationary in a long-term sense; recall that the design load combination is based on extremes, that is, load values occurring within a long reference period of time. Within a one year period of time, one might expect short-term and seasonal effects to be scaled down. For example, the time series of 3-hourly waves and winds (Larrabee and Cornell, 1981) can be viewed as stationary over a sufficiently long time period. As a result, each process can be defined by a point-in-time probability density function with mean μ_i and variance σ_i^2, and the autocorrelation function $R_i(t)$. Note that, as mentioned in 2.3, the "arbitrary point-in-time" value is simply a value that would be measured if the process were to be sampled at an arbitrary point-in-time. As shown in Fig. 3.1, the point-in-time pdfs may contain an impulse at zero intensity, representing the probability that the process is inactive at sampling time.

Suppose then that two environmental processes $D_1(t)$ and $D_2(t)$ have been recorded over a long period of time. The corresponding load processes (2.17) are:

$$Y_1(t) = c_1 D_1(t), \text{ and } Y_2(t) = c_2 D_2(t) \tag{3.1}$$

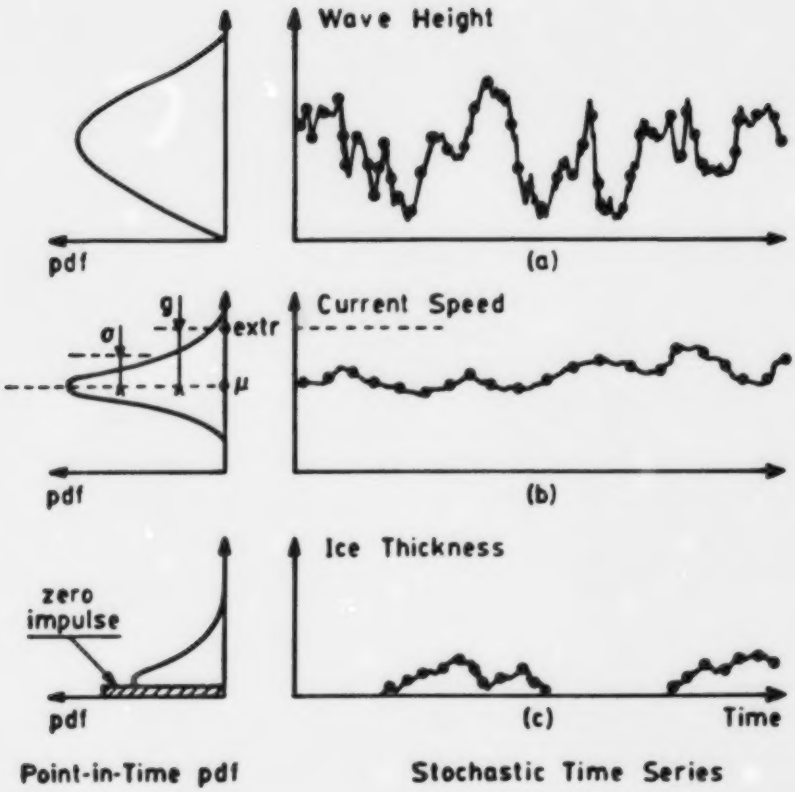


Fig. 3.1. Illustration of Point-in-Time pdfs

The pairs of data points $(d_1, d_2)_i$ can be shown in a scattergram or in a joint frequency table. The sample means and variances, and the sample correlation coefficient r_{12} may be calculated; also, if likely, the hypothesis of stochastic independence may be tested using contingency table techniques.

If the environmental processes were acting separately, then the extremes would contain all the information required by the designer:

$$e_1 = \text{extr } D_1 = \mu_1 + \sigma_1 g, \tag{3.2}$$

$$e_2 = \text{extr } D_2 = \mu_2 + \sigma_2 g, \tag{3.3}$$

and, using (3.1),

$$x_1 = \text{extr } Y_1 = c_1\mu_1 + c_1\sigma_1 g, \tag{3.4}$$

$$x_2 = \text{extr } Y_2 = c_2\mu_2 + c_2\sigma_2 g, \tag{3.5}$$

where extr(·) denotes a prescribed extreme value of the process (·). For example, e_1 and e_2 are the 100-year return period values of the processes D_1 and D_2 (note that the definition of "extr" differs from "max" (2.20): the latter refers to the largest random variable in a time series and is, itself, random, whereas the former denotes one particular value determined on the basis of the extremal pdf of the maximum); μ_i and σ_i are the mean and standard deviation of the environmental point-in-time pdf and g, as illustrated in Fig. 3.1b, is a non-dimensional extreme value expression that is a function of (Der Kiureghian, 1979):

1) the type of point-in-time probability distribution associated with the environmental process; and

2) the length of the period of time considered.

Important for the present analysis is the fact that g is generally not a function of μ_i and σ_i, provided that the processes considered have the same type of point-in-time pdf and provided that the extreme value is characterized using the same period of time (the latter condition is always satisfied). Expressions for g as a function of the type of distribution and the timespan can be found, for example, in Dept. of Energy (1987) for the normal pdf, in Krishnaiah and Rao (1969) and Breitung (1982) for the gamma pdf, and in Der Kiureghian (1979) for a general discussion. Assuming, in the remainder, that both processes are Gaussian, that is, they have a normal point-in-time pdf, then the total load effect time series Y(t) is the sum of the processes (3.1):

$$Y(t) = Y_1(t) + Y_2(t), \text{ or}$$

$$Y(t) = c_1 D_1(t) + c_2 D_2(t) \tag{3.6}$$

The combination load effect Y(t) is also Gaussian with the following mean and variance:

$$\mu_Y = c_1\mu_1 + c_2\mu_2, \tag{3.7}$$

$$\sigma_y^2 = c_1^2\sigma_1^2 + c_2^2\sigma_2^2 + 2r_{12}c_1c_2\sigma_1\sigma_2 \tag{3.8}$$

These results follow from the standard expressions for the moments of the sums of random quantities; r_{12} is the correlation coefficient of the two environmental processes. According to the principles set out in the previous chapter, the specified design load x is to be based on an extreme value of the combined load process; since the point-in-time pdf is of the same type as the individual point-in-time pdf and since the extreme value is to be based on the same return period, the design value is, similarly to (3.4) and (3.5):

$$x = \text{extr } Y = \mu_Y + \sigma_Y g. \tag{3.9}$$

Substituting (3.7) and (3.8) into (3.9) yields:

$$x = c_1\mu_1 + c_2\mu_2 + (c_1^2\sigma_1^2 + c_2^2\sigma_2^2 + 2r_{12}c_1c_2\sigma_1\sigma_2)^{1/2}g \tag{3.10}$$

It can be checked that if the total load effect is due only to the first environmental process ($c_2 = 0$), then $x = x_1$ as in (3.4), with a similar conclusion when $c_1 = 0$. The square root term within brackets can be rearranged to obtain:

$$(.)^{1/2} = (c_1\sigma_1 + c_2\sigma_2)\left(1 - \frac{2(1-r_{12})c_1c_2\sigma_1\sigma_2}{(c_1\sigma_1+c_2\sigma_2)^2}\right)^{1/2}. \tag{3.11}$$

The second term under the square root is always smaller than unity; as a matter of fact, it is close to zero in most practical applications. Hence, the Taylor expansion of (3.11) may be used and simplified to retain only the first two terms:

$$(1-\beta)^{1/2} \simeq 1 - \frac{\beta}{2} - \frac{\beta^2}{8} - \ldots \leq 1 - \frac{\beta}{2} \tag{3.12}$$

since $\beta^2/8$ is a very small, but positive number. Consequently, (3.10) transforms into the following expression, using (3.4), (3.5) and (3.12):

$$x \simeq x_1 + x_2 - \frac{(1 - r_{12})\, c_1c_2\sigma_1\sigma_2 g}{c_1\sigma_1 + c_2\sigma_2} \tag{3.13}$$

Alternatively, the specified <u>combined</u> load x, can be expressed in terms of the prescribed extreme environmental values e_1 and e_2 (3.2 and 3.3), the correlation coefficient r_{12} between the two environmental processes, and the point-in-time means of the processes μ_1 and μ_2 using (3.2) and 3.3):

$$x \simeq c_1e_1 + c_2e_2 - \frac{(1-r_{12})\, c_1c_2(e_1-\mu_1)(e_2-\mu_2)}{c_1(e_1-\mu_1) + c_2(e_2-\mu_2)} \tag{3.14}$$

The structural influence coefficients c_i really indicate "how much" the environmental process i contributes to the design load effect under consideration. It is important to know the relative proportion of the contributions 1 and 2; this can be expressed by the factor λ, which will be defined as:

$$\lambda = \frac{x_2}{x_1} = \frac{c_2 e_2}{c_1 e_1} \tag{3.15}$$

Thus, when $\lambda = 0$, the total load effect is entirely due to process 1, while $\lambda = \infty$ corresponds to the case where only process 2 contributes to the combined loading. Clearly, our objective is to ensure that engineers be provided with safe and economical design values over the entire range $0 < \lambda < \infty$, that is, no matter which environmental process is dominant. Equation (3.10), or its slightly approximate but more transparent form (3.14), is a means to investigate how the total design load value varies with λ. Figure 3.2 illustrates this situation.

Figure 3.2 also shows that for full positive correlation, $r_{12} = 1$, the total design load becomes $x = c_1 e_1 + c_2 e_2$, which is represented by the straight line connecting the two individual extreme values. Since the third term in (3.14) is always negative (recall that $-1 \leq r_{12} \leq +1$), the "design combination curves" for any other value of the correlation coefficient must lie below this straight line. Given the environmental data statistics e_1, e_2, μ_1 and μ_2 as well as λ and r_{12} (3.10) and (3.14) allow us to determine the design load combination.

The type of figure 3.2 proves to be a very useful tool for design engineers. It shows how the combined specified load effect varies as a function of the proportion factor λ, the intensities of the individual processes and their correlation.

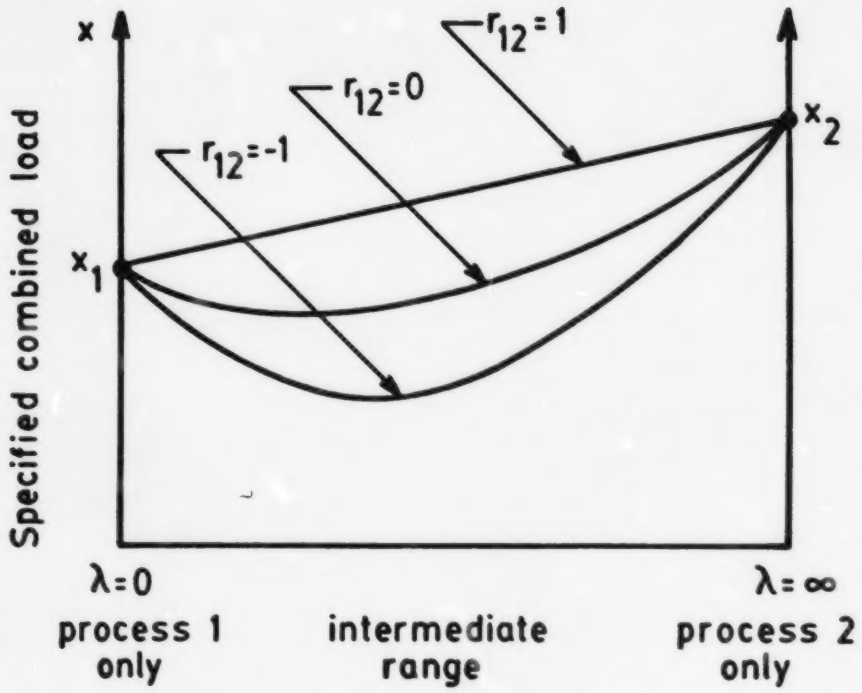


Fig. 3.2. Illustration of the Variation of the Combined Design Load with the Relative Proportion of the Two Contributing Loads

3.2 Comparison with Turkstra's Format

The conceptual model developed in (3.1) can also be used to investigate the efficiency of Turkstra's LC design criterion. According to Section 2.3, the Turkstra method relies on determining the largest load value corresponding to the combined action of each process acting, in turn, as a principal process together with the companion values of the other processes. In the case of two environmental processes, the equation (2.8) becomes:

$$\begin{aligned} x^* &= \max\ (x_1 + x_{21};\ x_2 + x_{12}) \\ &= \max\ (c_1 e_1 + c_2 e_{21};\ c_2 e_2 + c_1 e_{12}) \end{aligned} \tag{3.16}$$

where the asterisk refers to the fact that x is the specified load value determined by using Turkstra's rule. In (2.10) the important principle was introduced which states that the companion value e_{ij} of process i is equal to the mean conditional probability of the process i, given that the principal process j takes on its specified extreme value e_j. Because stationary Gaussian models have been assumed, the textbook result that the conditional mean of a bivariate normal pdf is linear in its conditional value,

$$\mu\ (Z_1 | z_2) = \mu_{Z_1} + r_{12} \frac{\sigma_1}{\sigma_2}\ (z_2 - \mu_2)$$

may be used to write the companion value (2.10) as:

$$\begin{aligned} e_{ij} &= \mu(D_i | D_j = e_j) \\ &= \mu_i + r_{ij} \frac{\sigma_i}{\sigma_j}\ (e_j - \mu_j) \end{aligned} \tag{3.17}$$

Substitution of e_{12} and e_{21} in (3.16) results in:

$$\begin{aligned} x^* = \max\ (&c_1 e_1 + c_2 \mu_2 + r_{12}\ c_2\ \sigma_2\ (e_1 - \mu_1)/\sigma_1; \\ &c_2 e_2 + c_1 \mu_1 + r_{12}\ c_1\ \sigma_1\ (e_2 - \mu_2)/\sigma_2\ ) \end{aligned} \tag{3.18}$$

Using the identities (3.2) and (3.3), we obtain:

$$x^* = \max \left(c_1 e_1 + c_2 e_2 - (1 - r_{12})\, c_2 (e_2 - \mu_2);\right.$$
$$\left. c_1 e_1 + c_2 e_2 - (1 - r_{12})\, c_1 (e_1 - \mu_1) \right) \qquad (3.19)$$

This design curve can also be plotted in a figure similar to Fig. 3.2. Clearly, (3.19) consists of two straight lines in such a diagram, as reflected by Fig. 3.3. The lines pass through the points x_1 at $\lambda = 0$ ($c_2 = 0$) and x_2 at $\lambda = \infty$ ($c_1 = 0$). More importantly, the slopes of these lines are exactly equal to the slopes of the true specified loads (3.10) at both extremities of the diagram, i.e. the following identifies are obtained:

$$\left(\frac{dx}{d\lambda}\right)_{\lambda=0} = \left(\frac{dx^*}{d\lambda}\right)_{\lambda=0} \qquad \left(\frac{dx}{d\lambda}\right)_{\lambda=\infty} = \left(\frac{dx^*}{d\lambda}\right)_{\lambda=\infty} \qquad (3.20, 21)$$

where (3.10) and (3.19) are used to compute the left-hand and right-hand side slope, respectively. In the combination diagram (Fig. 3.3) this result is reflected by the fact that the Turkstra lines are the tangents to the true design curve at the two single load case points. The following conclusions may be drawn (Fig. 3.3):

(1) Turkstra's rule is very satisfactory in the regions of very low or very high λ-values, that is, if any of the two loads is distinctly higher than the other one.

(2) The higher the coefficient of correlation r_{12}, the better the agreement between the "true" and the Turkstra design load. In all practical engineering LCs, r_{12} is a positive value and, although intensive data analysis will have to cast more light on this issue, it is likely that most correlation coefficients lie closer to +1 than to 0; this is also evident from Table 2.1. Also, the very critical offshore load combination of wind and waves is generally associated with a point-in-time correlation coefficient close to +1. Consequently, Turkstra's rule performs very well for these LCs.

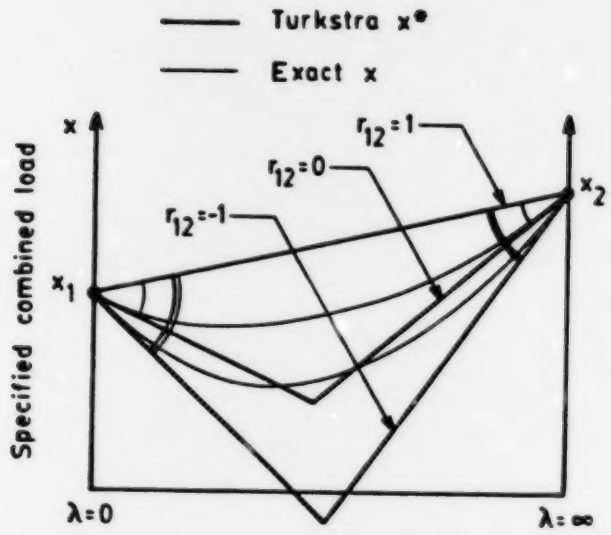


Fig. 3.3. Comparison with Turkstra's Rule

3.3 Uncertainties

So far, the assumption was made that the transformation of environmental event (e.g. wave height) into load (e.g. the drag force on a structural member) did not involve the introduction of uncertainties. In reality, the use of a load model such as Morison's wave force model is invariably associated with non-negligible model uncertainties (Davenport, 1982; Lloyd, 1985; Naess, 1982; Soares and Moan, 1982). For example, consider the equations (3.1), (3.2) or (3.6); instead of putting:

$$Y(t) = c_1 D_1(t) + c_2 D_2(t),$$

we must now take into account the fact that the c-factors are based on (many) uncertain assumptions regarding load-event transformation. As a result, we really deal with the following equation:

$$Y(t) = C_1 D_1(t) + C_2 D_2(t) \tag{3.22}$$

where C_1 and C_2 are, themselves, random quantities. Accordingly, the conceptual model developed in Section 3.1, together with the Turkstra approximation described in Section 3.2, can be modified to account for uncertainties by introducing probability distributions for the structural influence coefficients.

Load-event model uncertainties have been used extensively in previous calibration studies (Davenport, 1982; Maes 1986b, 1987) as well as in applied data analysis (Maes, Muir and Swail, 1987). These studies show that they can contribute significantly to the output variables. Another set of uncertainties is connected to the relationship between loads and load effects. These uncertainties are due to assumptions regarding structural dimensions, boundary conditions, load application, stiffness, and structural analysis in general. They are generally less important than the ones associated with environmental loading assumptions, but they can equally well be included in the modelling of the random variables C_1, C_2, ... C_n

The main conclusions of this section are summarized as follows:

1. it is of prime importance to account for both model and analysis uncertainties;

2. data regarding the variability of the associated coefficients are available in technical reports;

3. during data processing, it is essential to consider equations of the type (3.22), that is, with random instead of constant structural influence coefficients.

3.4 The Use of Correlation Measures

In the previous sections, the correlation coefficient r_{12} has been used as a tool to model stochastic dependence between two environmental processes. Indeed, in many fields, particularly the biological and social sciences, where basic laws are difficult to derive otherwise, it is common to measure repeatedly two variables which are suspected or hypothesized to be related and then to estimate their correlation coefficient. If the coefficient is near unity in absolute value, strong dependence is assumed verified; if the coefficient is low, it is concluded that one variable has little or no effect on the other. The coefficient is easily determined from a set of environmental data pairs $(d_1, d_2)_i$ as follows:

$$r_{12} = \frac{\Sigma(d_{1i} - \bar{d}_1)(d_{2i} - \bar{d}_2)}{(\Sigma(d_{1i} - \bar{d}_1)^2 \Sigma(d_{2i} - \bar{d}_2)^2)^{1/2}} \tag{3.23}$$

However, the limitations of the correlation coefficient as a basic parameter must be clearly understood. The coefficient (3.23) essentially measures the degree of linear relationship between the two series of observed values. For example, a second-degree functional dependence might go undetected with ($r_{12} = 0$), in certain cases. It is also important to appreciate the fact that the conclusions deduced from its use do not depend on the shape of the joint probability distribution.

A very good discussion about associating small correlation with weak dependence, where in fact the opposite is true, is given in Benjamin and Cornell (1970). This study also addresses the converse effect, namely spurious correlation which may invite unwarranted conclusions of a cause and effect relationship between variables when, in fact, none exists.

In the light of this discussion, it is recommended that in the course of environmental data analysis, other measures of correlation are also applied. It must be recognized that none of these measures are as powerful as r_{12}, but they can be indicative of additional dependencies which the correlation coefficient may not be

able to detect on its own. As an example, we have the rank correlation measures in which one of the two data series is ranked in increasing order of magnitude and the resulting data pairs are replaced by their final differential ranking; Spearman's coefficient is especially appropriate as it does not depend on the assumption of normality between the two variables involved.

Consequently, although the correlation coefficient provides a very useful measure of dependence between variables, we must be careful in its interpretation. Large values of r_{12}^2 imply strong stochastic dependence and a near-linear functional relationship, but not necessarily a cause-and-effect relationship. Small values may result from the predominance of other sources of variation (and hence low stochastic dependence), or if a functional relationship exists, from its lack of strong linearity.

3.5 Specific Requirements

In Chapter 2, three fundamental requirements were identified for obtaining, developing and calibrating effective load combinations for engineers. Careful planning of environmental data analysis and processing was considered to be essential in achieving this objective. The preliminary analysis described in the present Chapter leaves us now well prepared to recommend the LC parameters needed to implement the three-phase work plan outlined in Table 2.2, as well as to outline the analysis required to derive these parameters.

a) Work Plan Task I: The generation of LC values for use in connection with design codes.

Required Output

(1) For each desired individual environmental process i:

the specified load value x_{si}, at a prescribed annual probability of exceedance η.

(2) For each desired combined pair (i, j):

the companion load values

x_{ji} (companion j + principal i)

$\bar{x}_{ij}$ (companion i + principal j)

Analysis Required:

(1) - extreme value analysis (X = max Y during one year) of the product (3.22), $Y = C_i D_i$, where C_i encapsulates load-event and load-load effect transformation uncertainties;
- determine the load x_s at a probability of exceedance η.

(2) - apply a statistical test of stochastic independence to the data (i,j);
- use Turkstra's approach to establish to which class in Table 2.1, the load combination (i,j) belongs;
- depending on whether (i,j) are independent, mutually exclusive or dependent, choose the companion value as the mean point-in-time (2.12) (the mean of all the individual D_j data), zero (2.11), or the specified extreme (2.13), respectively.

Discussion

The data analysis required is minimal; no joint or conditional probability distributions need to determined; only a contingency test for independence is carried out to derive the appropriate LC class. The designer can plug the derived values straight into suitable LC rules.

(b) Work Plan Task 2: The generation of detailed statistical LC parameters related to the metocean environment.

Required Output

For each environmental process i:

- the point-in-time mean and variance μ_i, σ_i^2, and the type of pdf;
- the point-in-time mean and variance of the associated load μ_Y, σ_Y^2, and the type of pdf;
- the parameters of the extreme value distributions of environment and load;
- the specified extremes x_{si} and e_{si};
- the parameters of the pdfs of all the uncertainties C_k;
- the correlation coefficients with all the other processes r_{ij};
- LC design diagrams as in Figure 3.2 and 3.3 for the site considered, using both a full analysis and Turkstra's approximation;
- selected marginal and conditional means, variances and extremes.

Analysis Required

A model similar to the one presented in Chapter 3 will yield sufficiently accurate results. The analysis can be refined by selecting different types of pdf instead of Gaussian models. Essential in deriving the LC design diagrams for varying λ values, are formulae (3.10), (3.14) and (3.19) or their re-worked versions, if allowance is made for different probability models and the uncertainties associated with the C coefficients.

Discussion

The final product essentially consists of the self-evident LC design diagrams (Figures 3.2 and 3.3). They allow the designer to determine the design load at a range of points within the structure (only the C-coefficients change and this only affects λ). They can also be used to assess the performance of

Turkstra's rule and the conservatisms associated with its use, which can readily be translated into economic benefit/loss. The software required to implement the environmental data processing is self-contained and relatively straightforward.

(c) Work Plan Task 3: The development of probabilistic models of joint environmental processes, with the objective of improving/developing/calibrating LC design criteria.

As discussed in the second chapter, this task requires the development of full probabilistic models for joint environmental processes, loads and model uncertainties. Two analytical options are available:

(1) A simplified joint time-series analysis either by the Borges-Castanheta method (1971) or the point crossing method (Larrabee and Cornell, 1981), both of which were discussed in Chapter 2. Advanced joint pdf techniques are, in this way, avoided.

(2) The analysis of severe storms and the determination of extreme loads by a joint compounding method. Traces of offshore wind, wave and current sampled at about 1 Hz need to be available during certain storms, in order to conduct such an analysis. Battjes (1979) multi-parameter approach would be quite suitable to derive the characteristics of the load response.

Evidently, Task 3 involves a concentrated joint effort on behalf of both data specialists and engineers. The benefits of such an in-depth analysis, however, would be immeasurable, and the experience gained in applied meteorological and oceanographic data analysis would be unparallelled.

4. ASSESSMENT OF THE APPLICABILITY OF CANADIAN OFFSHORE ENVIRONMENTAL DATA BASES

4.1 Description of the Available Data Records

In the present section, the existing Canadian offshore data sets for winds, waves, currents, sea ice, icebergs and earthquakes are identified together with the agencies which archive the data. As most of the data sets are very well documented and are readily accessible, their applicability to engineering load combination design can be assessed efficiently and without great difficulty. In what follows, only the metocean parameters which are used in the analysis of L.C. are described. The data sets are grouped according to their archiving centres. A general discussion of each data set is followed by the names and phone numbers of the scientists contacted and the material received.

(a) The Canadian Climate Centre (Atmospheric Environment Service, Downsview, Ontario)

The Canadian Climate Centre at AES operates a series of user-friendly marine climate and ice information systems. The objective of the Centre is to provide a capability for easy and rapid analysis of marine climate and ice data in a form appropriate for decision makers, both in industry and in government regulatory agencies. Four systems are particularly relevant to the present study. The powerful Marine Statistics Software (MAST 1985) provides users with various data processing facilities, tabular and graphical products and basic statistics. CONAN is a software package for producing publication quality graphics of user-defined statistics in the form of contour maps. DUST provides the user with several functions for duration statistics and extreme value analysis. The term "duration statistics" is not commonly used by structural engineers; it refers to up-crossing frequencies of a specified level and their duration in time. Finally, there is CRISP which operates on data associated with sea ice concentrations and their occurrence frequencies.

The information systems, which were found to be efficient and user-friendly, provide good quality statistical products in the form of tables, maps and graphs. It lies outside the scope of this study to describe and appraise all the features of the software; instead, an excellent overview of the Climate Information Systems is contained in a reference by Saulesleja et al. (1985).

MAST, DUST, CONAN and CRISP access a variety of different data which are useful for offshore engineering operations and design. Since current and oceanographic data are collected by Fisheries and Oceans Canada, the following AES data sets are directly applicable to LC design:

- wind data sets
- wave data sets
- ice concentration data sets
- high rate short-term wind measurements.

Except for ship reports, buoys and a limited number of Drill Rig synoptic reports, all of the wind data sets are hindcast products. In Table 2.1, a summary is given of each data set in terms of the variables used, the areal and temporal coverage and the origin of the data. The quality of the data has been investigated extensively in specialized studies (Swail et al., 1984) and has been documented in a number of papers referenced in the Marine Climate Directory (AES, 1987) of data sets and services. In many cases, the output product will need to be converted into the appropriate wind speed value used in load combination criteria; CSA (1987), for example, uses the sustained wind velocity averaged over 10 minutes and at a height of 10 m above sea level (it allows, however, for intermittent observations); transformation procedures are given in Appendix C of the S471 standard. In any event, the recommendations provided in quality control studies of wind data sets will need to be taken into careful consideration, in order to work with reliable environmental parameters.

TABLE 4.1. WIND DATA SETS

DATA SET Including Variable Defined	AREAL COVERAGE East Coast	West Coast	Arctic	GRID SPACING (if applicable)	EXTENT IN TIME (yrs)	FREQUENCY IN TIME	ORIGIN OF THE DATA
AES Geostrophic Wind Climatology (geostrophic wind)	X	X	X	381 km	42	6 hrs.	From surface pressure data
WES Waterways Experiment Station (19.5 m level wind blended with ship observations)	X		(Hudson Bay)	222 km(*)	20	3 hrs.	U.S. army wind hindcast (+ Blending)
SOWM Wind Climatology (19.5 m level wind)	X	X		300 km	20 (Atlantic) 13 (Pacific)	6 hrs.	Spectral Ocean Wave Model Hindcast (+ Blending)
MEDS (Resio model) (19.5 m. level wind)	X			222 km	1	6 hrs.	Experimental hindcast. Highly variable results
NEDN (surface winds)	X	X	X	381 km	14	6 hrs.	Real Time Hindcast (+ Blending)
SHIP WIND REPORTS	X	X	X	-	30 (possibly larger)	-	Estimated and measured. Variable quality
DRILL RIG REPORTS	X		X			3 hrs.	Synoptic reports
BUOY WIND REPORTS	X	X		-	10	3 hrs.	Synoptic reports
MEDS (ODGP model) (19.5 m.level wind)	X			139 km 69 km	3	6 hrs.	Continuous 3-year hindcast using 006P model (+ Blending)
Ben Nevis Wind Data (1 min. mean)	Ben Nevis Well				3/4	1 min.	Anemometers on rigs

(*) only selected points have been converted.

Apart from (a) the measured wave data archived at MEDS, which are discussed in a subsequent paragraph, (b) a series of half-hourly significant wave height and average wave period measurements at Ben Nevis (see wind data set), and (c) the ship, buoy and rig wave reports, all the wave data sets are derived by hindcast. The SOWM, NEDN and WES wave data have similar origins, areal coverage and time characteristics as the corresponding wind data sets (Table 4.1). The METOC wave data for the NW Atlantic contain grid point significant wave height values, every 12 hours, based on available wave reports together with a Bretschneider - modelled wave using METOC's own surface analysis products. Ship wave reports will not be considered further since several quality controls have shown that they exhibit considerable variability.

The calculation of ice loads on offshore structures requires an extensive number of parameters ranging from ice concentration to thickness, floe size, ridge dimensions, speed, direction of movement, density, micro structure and mechanical properties. Presently, the Canadian Climate Centre only archives weekly ice concentration and ice age derived from areal patrols, satellite imagery and surface observations. Provided that concurrent data are used for the other ice variables, then wave-ice and wind-ice load combinations can be studied. This does not preclude investigation of dependencies between archived variables such as wind speed and direction, and ice concentration; such an analysis is very useful from the point of view physical modelling of environmental variables, but there is no direct link to the joint behaviour of extremes of these variables. In any event, it is essential to link CRISP with other ice data sets in order to undertake a meaningful analysis of load combinations.

The Ice Climatology and Applications Division of AES in Ottawa is the agency responsible for the collection and archiving of ice data in Canadian waters. Their archives (1959 till present) include % coverage, floe sizes, ice types and weekly concentration and they provide CRISP and CSIIS (see further) with digitally extracted data. Very few data on icebergs are available.

As indicated in the previous chapter, the recommended Work Plan Task 3 requires a full joint probabilistic analysis of relevant environmental processes

1. HUSKY BOW VALLEY RIG

Bow Drill III rig, North Ben Nevis well
water depth 85 m
wind sampling interval 1 second
record length 20 minutes (2 ten minute blocks with 45 sec gap)
data available at AES for January 3-31, 1985
mean wind speeds up to 31 m/s
anemometer height 82.6 m
wave and current data are available from MEDS/BIO

2. MOBIL RIG

Rowan Juneau rig, Venture B-13 well
water depth 25 m
wind sampling interval 0.5 second
record length 20 minutes (first 17 minutes saved)
data available at AES for February to June 1981
mean wind speeds up to 25 m/s
anemometer height 54 m
wave and current data are available from MEDS/BIO

Table 4.2. High Rate Wind Data Sets

and loads. One of the options given (option C.2 in Section 3.5) is to compound a multiparameter response during severe storms. Traces of offshore wind sampled at 1 Hz are available at AES for the two sites given in Table 4.2. Concurrent wave and current data are available from MEDS and BIO.

Contacts:	- Val Swail	416-739-4347:	all AES data sets
	- Tom Agnew	416-739-4385:	CRISP data sets
	- Dave Mudry	613-995-6730:	ice data archives at the AES Ottawa Ice Climatology Division

Material Received:

- Marine Climate Directory - Data Sets and Services, Internal Report No. 87-2, Hydrometeorologic Division of the Canadian Climate Centre, June 1987.

- Marine Statistics (MAST) Software Package - User's Manual, Hydrometeorology Division of the Canadian Climate Centre, Version 5.0, April 1985.

- Sea Ice Climate Information System (CRISP) - User's Manual, The Canadian Climate Centre and the Ice Branch (AES), Version 1.0, November 1986.

- Duration Statistics System (DUST) - User's Manual, Hydrometeorology Division of the Canadian Climate Centre, April 1985.

- Contour Analysis System (CONAN) - User's Manual, Hydrometeorology Division of the Canadian Climate Centre, April 1985.

- Several sample output plots and tables.

- High Rate Wind Data Sets.

- Swail et al. (1983).

- Saulesleja et al. (1985).

(b) The Marine Environmental Data Service (MEDS), Dept. of Fisheries and Oceans, Ottawa.

MEDS is Canada's national centre for the management and care of oceanographic data, which include station data (physical and chemical variables), tide and water level data, drifter data and also wave data and drill rig observations, which are important to the present study. The data are accessible through a system 2000 DB and display and analysis software is available. Specialized data analysis requiring user-defined operations must be carried out on a customized basis under MEDS' supervision.

Most of the wave data are obtained using waverider accelerometer buoys from 20-minute records every three hours at 7.5Hz. The wave measuring stations are well documented; the archives contain the length in time of the data record and an evaluation of the data quality associated with the instrument used. Further quality control is left to the user.

The digitized wave records (decimated to 2 pts/sec) are maintained separately from the more frequently accessed analysis products (significant wave height, peak period, etc.). Routinely available are exceedance diagrams, peak period histograms, scatter diagrams, spectrum plots and time history plots.

Directional wave data are available from oil rigs but only during the last few years. Hindcast wave data (cf. AES) are also accessible. Drill rigs are the source of many combined environmental measurements. The regulatory agency COGLA (Canadian Oil and Gas Lands Administration) issues strict guidelines for the measurement and the recording of metocean variables during offshore drilling programs (see reference enclosed). MEDS functions as the archivist of all these data. The inventory contains about 350 entries of short term drill rig data sets.

Contacts: - Andre Bolduc 613-990-0231
- Jean Gagnon 613-990-0240

Material Received:

- MEDS - User's Guide, Marine Environmental Data Service, Fisheries and Oceans, April 1981.

- MEDS - Historical Wave Measuring Stations - Station Locations Summary, Marine Environmental Data Service, Fisheries and Oceans, May 1986.

- Printout of the "Current Meter Data Report"

- Printout of the "COGLA Status Report"

- Physical Environmental Guidelines for Drilling Programs in the Canadian Offshore - Metereology and Ice Tape Formats and Forecast Verification - Environmental Protection Branch, COGLA, Sept. 1985.

(c) The Bedford Institute of Oceanography (BIO)

BIO maintains an archive of current meter data for the Atlantic East Coast, the Gulf of St. Lawrence and the Eastern Arctic from 1960 to the present. Figure 4.1 shows the geographical distribution of 60 station years of current meter data on a $1^{\circ} \times 1^{\circ}$ grid. Although there are apparently many "holes" in the spatial coverage, the archive forms one of the largest current data bases in the world. A large proportion of the data is contributed by drill rig measurements, particularly on the Grand Banks. Limited data processing is available but it is generally performed on request only, by local staff. The inventory includes sounding and instrument depth, the length of the record, the frequency of measurements and the mean, minimum, maximum and standard deviation of the N-S and E-W components of the current. (Engineers should be aware of the fact that a Northerly current is directed towards North, unlike a Northerly wind.)

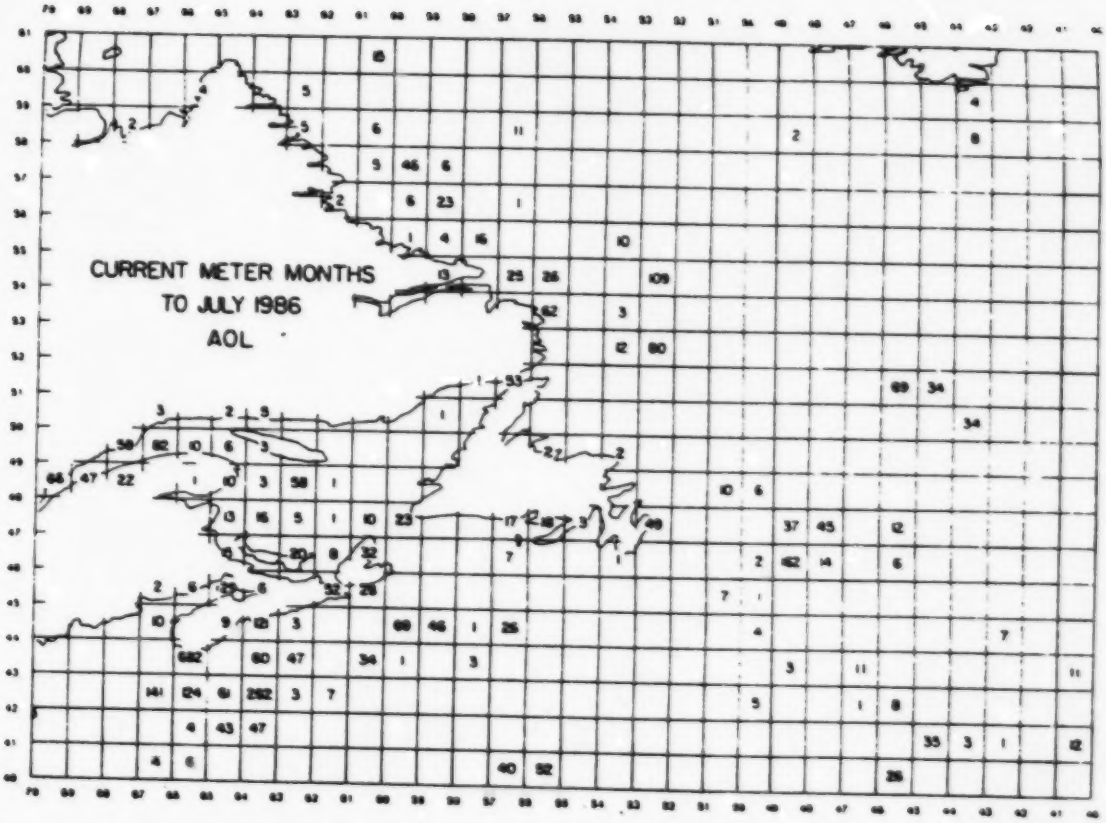


Figure 4.1. Number of Months of Current Meter Data by 1^{o} x 1^{o} square, Archived at AOL as of July 1986 (Courtesy of D. Gregory, AOL)

The Institute performs research in several branches of oceanography. For example BIO maintains a data record on ice concentration and ice drift. Icebergs are also studied extensively from the viewpoint of the physical modelling of trajectories and kinematics. Although iceberg speed and direction are important variables for design, there is a definite need to maintain an archive on other physical and mechanical iceberg parameters.

Contacts: - Brian Petrie 902-426-3809
- Doug Gregory 902-426-8931
- Stu Smith 902-426-2558

Material Received:

- Inventory of Current Meter Data, Bedford Institute of Oceanography, Fisheries and Oceans, January 1987.

(d) The Institute of Ocean Sciences (IOS), Sidney, B.C.

IOS is BIO's counterpart on the West Coast. It maintains the current meter data archive for all the Pacific locations. IOS has also performed extensive quality control of all the West Coast and Arctic physical oceanographical data, on a regional basis. The experience with Arctic data analysis is particularly relevant to the present study, with the growing interest in designing permanent production structures for the Beaufort Sea. IOS is also very familiar with the exploratory drill rig data acquired in this area. The reports sub-mentioned contain complete and specific information regarding these data sets.

Attention was drawn to the fact that the Beaufort Sea metocean regime cannot easily be modelled. A lot of bi-modal effects such as the succession of long active/quiet periods, will require a careful investigation of the joint probability models used for environmental parameters.

Contacts: - Paul Budgell 604-356-6330
- Brian Smiley 604-356-6551

Material Received:

- West Coast Data Inventory and Appraisal

Volume 1 (Part 1), 1985	Physical Oceanography
Volume 1 (Part 2), 1985	
Volume 2 (Part 1), 1986	Physical Oceanography
Volume 2 (Part 2), 1986	
Volume 3 (Part 1), 1986	Chemical Oceanography
Volume 3 (Part 2), 1986	

Canadian Data Report of Hydrography and Ocean Sciences No. 37, Institute of Ocean Sciences, Fisheries and Oceans.

- Arctic Data Compilation and Appraisal

Volume 1, 1982, Beaufort Sea,	Physical Oceanography
Volume 3, 1983, Northwest Passage,	Physical Oceanography
Volume 5, 1983, Baffin Bay,	Physical Oceanography
Volume 6, 1983, Queen Elizabeth Islands,	Physical Oceanography
Volume 7, 1984, Canadian Basin,	Physical Oceanography

Canadian Data Report of Hydrography and Ocean Sciences No. 5, Institute of Ocean Sciences, Fisheries and Oceans.

(e) The Centre for Cold Ocean Resources Engineering (C-CORE), St. John's, Newfoundland

C-CORE developed the Canadian Sea Ice Information System (CSIIS), a user-friendly software system which accesses various government and private data sources of different marine areas. Data include ice-coverage, ice movement, physical, mechanical and morphological properties. Since C-CORE is an engineering centre, it has been able to structure the Sea Ice System according to basic engineering needs. However, only routine statistical analysis products

are provided and many important parameters are insufficiently covered. In comparison with, for example, the MAST output products, the presentation of data and statistical parameters in textual and graphical form is considerably inferior.

Contact: - Eugene Guy 709-737-8354

Material Received:

- Canadian Sea Ice Information Systems - general information brochure and introductory letter.

(f) The Earth Physics Branch (EPB), Ottawa

In some regions of the Canadian offshore, earthquakes pose the most severe restrictions on the design of offshore structures. As a result, seismic loads need to be considered in load combinations. EPB archives all the Canadian seismographic data. They recently developed seismic hazard maps for Eastern Canadian Offshore Regions (the effort is presently being repeated for Pacific and Arctic regions). In the process, recurrence parameters were developed for distinct source zones in the Atlantic. These parameters are easily related to the mean arrival rates of earthquakes with a given magnitude, which in turn can be used to model load time series for the LC analysis.

Contact: - John Adams 613-995-5519

Material Received:

- Development of Seismic Hazard Maps for Eastern Canadian Offshore Regions, COGLA Technical Report Series No. 100, October 1987.

4.2 Applicability of the Data to Engineering Load Combinations

a) General Combinations

The applicability of the environmental data records to load combinations may readily be assessed in the framework of the suggested Work Plan (Table 2.2) and the associated specific approaches recommended in Section 3.5.

For each geographical region of interest, data sets for different variables, but for (approximately) the same site, must be subjected to one of the three analysis procedures outlined in each task of the Work Plan. Ideally, at least one of the data sets should consist of measured observations; careful consideration must be given to performing a joint probability analysis on wind and wave data obtained using the same hindcast (e.g. SOWM, NEDN or WES), since hindcast techniques are, themselves, based on functional dependencies between different environmental processes.

Consequently, provided that the data have been properly quality controlled and provided that they can be closely matched to other data sets covering the same geographical region at approximately the same time, every single data set listed in Section 4.1, is applicable to a load combination analysis. The only exceptions are the CRISP ice data which, as discussed before, cannot be related to loads, unless they are linked with other physical and mechanical ice parameter data archives. From the viewpoint of close affiliation between different data sets, the drill rig data measurement and collection programs are ideally structured, since wave, wind and currents are frequently recorded simultaneously. An important aspect of the analyses that are recommended to be performed is that the objective is not to establish or verify functional dependencies between metocean variables (e.g., wind and current), although, of course existing physical models can be used to derive the required parameters. The analyses will deal with extreme loads and, in order to determine safe and economic design load values, it is necessary to have an understanding of statistical correlations between the input variables.

Applicability also implies accessibility, especially at the level associated with the Task 1 Work Plan. It must be recognized that the needs of an engineer differ considerably from those of a weather forecaster or an oceanographer. When requesting (instant) load combination values, engineers will likely be interested in background information regarding the original parameters measured, their quality assurance and their sources. We may benefit from the experiences gained by the principal investigator (who is an engineer) in the course of the present study: the interaction with meteorologists and oceanographers at the several agencies was generally excellent. The inventories and user's guides issued by the CCC (AES) and MEDS are mostly very comprehensive.

Of the six agencies listed in Section 4.1, C-CORE and EPB, are probably most geared towards engineering applications, but the contributions of these agencies is minimal. AES is really quite versatile, considering the flexible structure of its data access software. This will be discussed further in the next subsection.

b) Software Requirements

The first requirement is to develop analysis software in accordance with the work plan recommendations. For example, if Task 1 (Section 3.5(a)) is being considered, then the additional software is limited to mean point-in-time values, and extreme value analysis, a statistical independence test, and a selection of three possible classes of companion values. The AES software packages MAST and DUST would already take care of the first two items in this list. Software associated with the other work plan tasks is more elaborate, but the overall layout is still quite straightforward.

The products resulting from the several load combination analyses can be represented in textual form (Tasks 1 and 2), but graphical output is also required for:

(a) data inspection (an example is given in Figure 4.2 where wind speed and wave height are plotted on a common time axis).

(b) the "design load combination diagrams" associated with Task 2.

(c) full graphical facilities for Task 3.

In this context, the software available at AES, is highly recommended. Frequently, the user is given the option to supply these programs with his/her own subroutines for analysis of user-derived parameters, such as load and companion values. Consequently, MAST, DUST, CONAN and CRISP are ideally suited for the applied data analysis associated with the prospective LC projects. An example of a joint frequency plot and diagram is given in Figures 4.3 and 4.4, respectively; the same kind of output format could be used for loads instead of metocean values.

The question has also been raised which agency would be better equipped to carry out LC analyses. As discussed, AES would be indicated from the viewpoint of available software facilities. This would bring about the inconvenience that MEDS, BIO, IOS and other data sets first need to be made compatible with the MAST format. MEDS, on the other hand, would also be a logical choice, because it archives all the data sets needed; however, MEDS itself does not routinely deal with winds or currents and would have to pass the analysis phase on to one of its technical groups at BIO or IOS. Alternatively, software packages may be developed independently and subsequently linked with the MEDS and/or AES archives.

High rate wind data sets from AES will also need to be crossmatched with MEDS wave and current data, if the storm-compounding technique is used (Task 3 - Section 3.5(c)). This will involve an important amount of modelling and software development, but, as mentioned before this project would be unique in its kind and would bring considerable benefits to LC design.

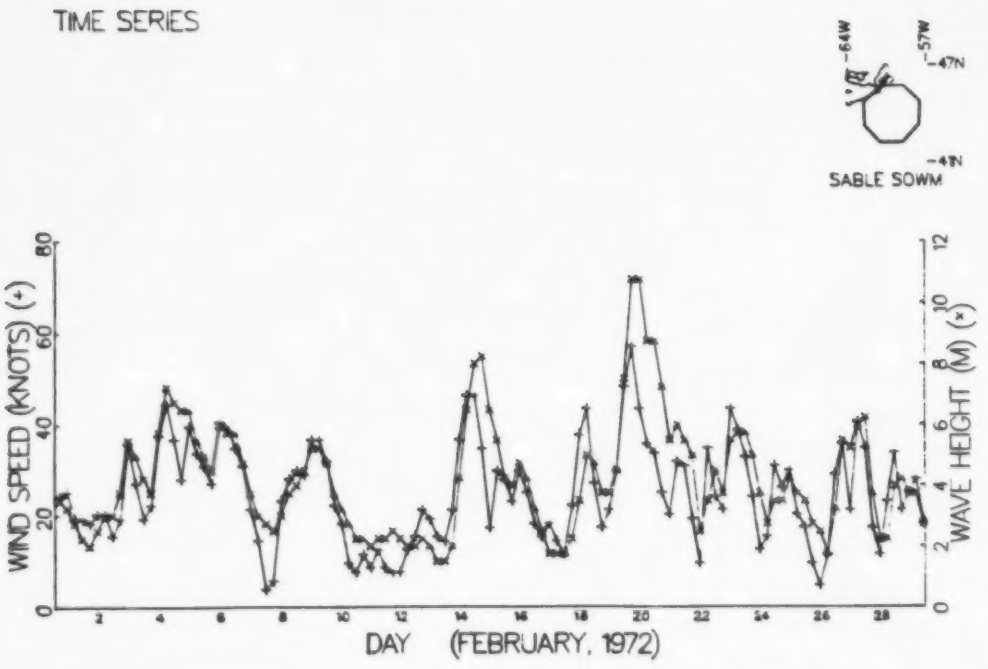


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Fig. 4.2. Sample Output of Six-Hourly Wind Speed and Wave Height Time Series at Sable, Using SOWM Data (MAST)

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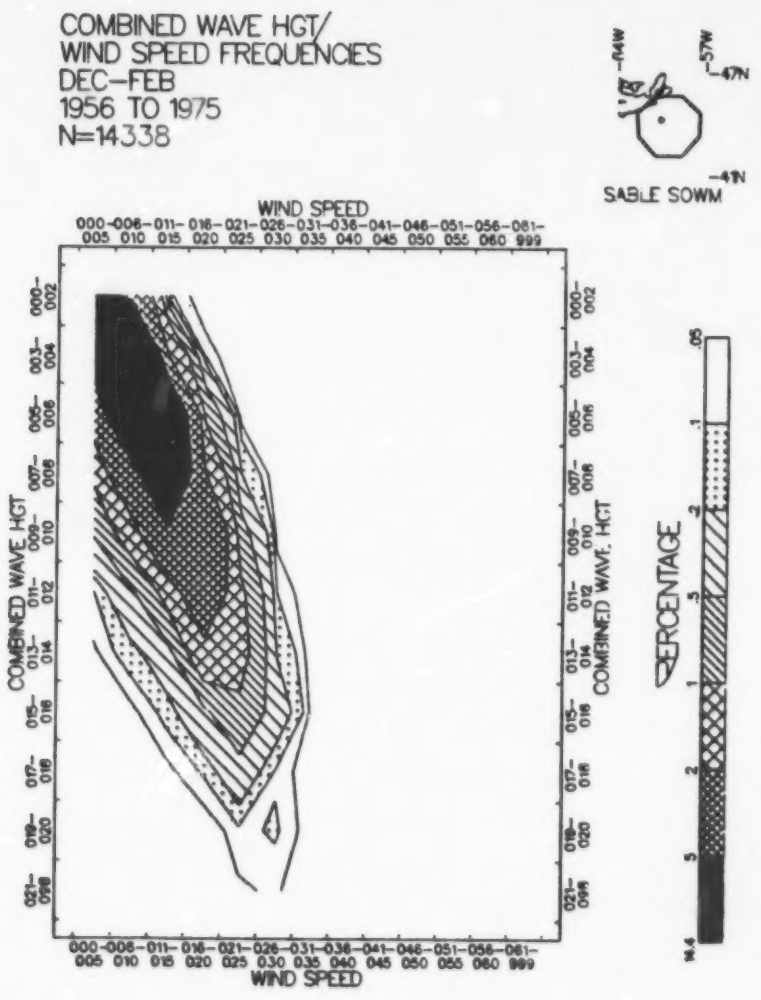

Fig. 4.3. Joint Frequency Plot of Combined Wave Height and Wind Speed at Sable, Using SOWM Data (MAST)

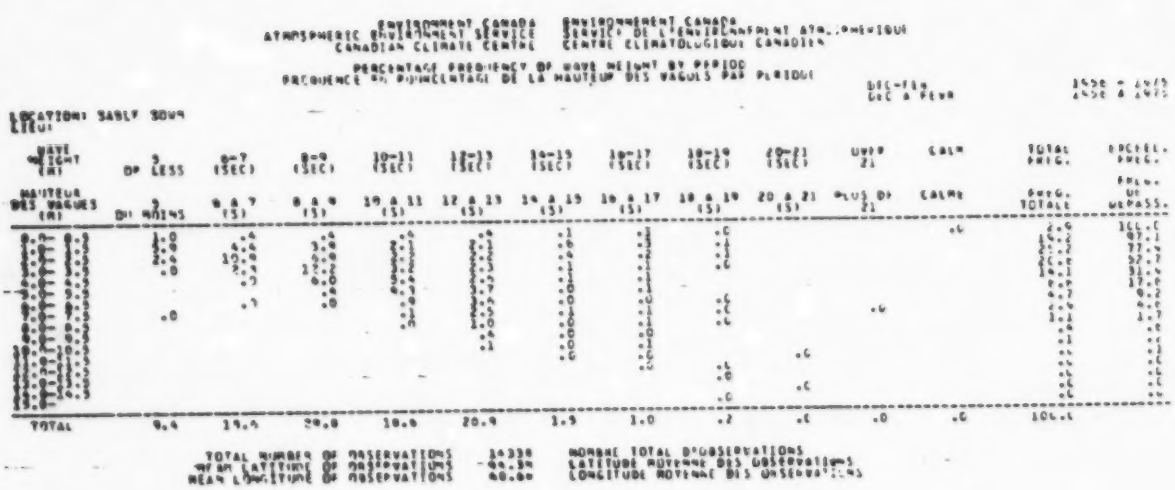

Fig. 4.4. Joint Frequency Diagram of Wave Height and Wave Period at Sable, Using SOWM Data (MAST)

c) Additional Recommendations

- Of all the environmental processes contributing to the overall load in a structural member, ice remains the most problematic. The determination of ice loads on structures requires a lot of variables to be considered. A lot of data exist in the private sector, some of them being protected by confidentiality agreements, but recently, strong efforts have been made to centralize these data (among others by the Dept. of Public Works). The ice parameters accessible at the agencies discussed in this study are useful for engineers, but cannot be used individually to determine ice loads. Again, this problem is not specific to load combination analysis, but to ice load data collection in general. CRISP, which is a powerful software package, should basically be extended to include the ice parameters presently listed in, for example, CSIIS, in order to produce meaningful engineering load measures. Alternatively, CRISP should be linked to ice-structure interaction programs.

- There is a great need for the additional measurement and/or collection of high rate simultaneous wind, wave and current data over extended periods of time (e.g. 2 months or, during storm events).

- A difficulty remains in the assessment of current data; critical loads on structural members generally occur close to the waterline penetration. However, surface currents are not routinely available and are not usually measured because of instrumental difficulties. However it is possible to add certain wind or wave correlated components to the deep-water currents which show little variation in time apart from tidal effects. This procedure needs precise physical modelling (surface current models are available at Coastal Oceanography) and careful verification.

5. CONCLUSIONS

The study of load combinations in structural design is particularly complex and involves careful consideration of factors related to several disciplines, such as:

- decision and utility theory,
- structural engineering,
- stochastic processes,
- extreme value analysis,
- meteorology and oceanography,
- applied data analysis.

The approach to LC varies widely, depending on which of the above fields is regarded as most fundamental to a practical and meaningful solution for engineers. The approach in the present study has been to put each of these fields in their proper perspective. For example, it is impossible to derive suitable LC values on the basis of a metocean data analysis only; by the same token, it is hardly worthwhile to develop sophisticated techniques on a purely theoretical basis, if environmental data are not available to supplement them.

The Canadian offshore data on wind, waves, sea ice, currents and earthquakes have been found applicable to the requirements of structural design engineers involved in obtaining and developing load combination criteria. It is sufficient to crossmatch data sets for different variables within the same geographical area. It is not particularly relevant, for example, if the hourly wind or the three hourly wind is used; these differences are to be accounted for in the transformation between environmental processes and loads. Also, the time series analyses required do not strictly necessitate that the data of different processes are recorded at exactly the same points in time. It is essential, however, to account for model and analysis uncertainties associated with the transitions from event to load, and load to load effect.

The software developed at AES is well suited for the analyses reassociated with

the requirements outlined in Section 2.5 and Table 2.2. It needs to be supplemented with specific LC techniques, but, as discussed in the recommendations contained in Section 3.5, the effort involved can be qualified as minimal (Task 1) and reasonable (Tasks 2 and 3). In reviewing the applicability of individual data sets, it appears that (1) a meaningful analysis of ice load data is to be considered problematic unless other data sets can be linked up to CRISP or CSIIS; (2) currents need to be carefully remodelled prior to computing associated loads; (3) appropriate statistical techniques, particularly time series, cross-correlation and extreme value analysis techniques, need to be applied on a case-by-case basis.

The Turkstra format for load combinations was closely examined in this study. It is generally a sound practical approach to LC design. Therefore, the recommendations associated with Work Plan Task 1 - to generate design values for use in connection with codified rules - are based on this format.

A conceptual analysis of the combined action of two or more random load processes also showed which data parameters are required for Work Plan Task 2. The main ideas of such an analysis can easily be translated in processing software, and the graphical representation of a LC design curve in the form of Figures 3.2 and 3.3, will be a valuable product for engineers.

Finally, a full analysis of joint environmental and load processes is also possible, as discussed under the Task 3 recommendations. This task must be accompanied by the continuing acquisition of high rate data on wind, waves and currents, e.g. on drill rigs. The analysis will be particularly useful for improving, developing and calibrating LC design criteria.

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